Variational Data Assimilation in Shelf Circulation Models

Alexander L. Kurapov
College of Oceanic and Atmospheric Sciences, Oregon State Univeristy, 104 COAS Admin Bldg., Corvallis, OR, 97331-5503
phone: (541) 737-2865 fax: (541) 737-2064 email: kurapov@coas.oregonstate.edu

Gary D. Egbert
College of Oceanic and Atmospheric Sciences, Oregon State Univeristy, 104 COAS Admin Bldg., Corvallis, OR, 97331-5503
phone: (541) 737-2947 fax: (541) 737-2064 email: egbert@coas.oregonstate.edu

John S. Allen
College of Oceanic and Atmospheric Sciences, Oregon State Univeristy, 104 COAS Admin Bldg., Corvallis, OR, 97331-5503
phone: (541) 737-2928 fax: (541) 737-2064 email: egbert@coas.oregonstate.edu

Award Number: N00014-08-1-0942
http://www-po.coas.oregonstate.edu/po/homes/kurapov/main.html
http://www.coas.oregonstate.edu/faculty/kurapov.html

LONG-TERM GOALS

The long-term goals of this research project are to advance data assimilation (DA) methods for coastal ocean circulation models. After several years of research focused on various aspects of advanced, variational DA with nonlinear coastal ocean models, we have come close to development of an optimal, versatile, and relocatable DA system based on a primitive equation model with a turbulence submodel. The system can be used efficiently both for operational needs (forecasting, search and rescue, environmental response) and for fundamental studies of coastal ocean dynamics. The modeling system will have the capability to assimilate time-series measurements from moorings and coastally-based high frequency (HF) standard- and long-range radars, satellite information (SSH, SST), and hydrographic survey data (including observations from underwater gliders).

OBJECTIVES

Scientific and technological objectives of this project include:

- Development of a data assimilation system that utilizes the advanced variational representer method with a nonlinear three-dimensional model of ocean circulation over shelf and in the adjacent interior ocean energized by coastal flows (a coastal transition zone, CTZ).
- Testing this data assimilation system with observations available along the Oregon coast.
- Understanding the impact of assimilating satellite observations (alongtrack SSH, SST composites) and in-situ observations (HF radar surface velocities, moored velocities, glider hydrographic

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Variational Data Assimilation in Shelf Circulation Models**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,College of Oceanic and Atmospheric Sciences,104 COAS Admin Bldg,Corvallis,OR,97331-5503**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**10**	

transects) to improve accuracy of prediction of the oceanic currents and hydrographic conditions, including short term (3-6 day) forecasts.

- Understanding co-variability of shelf and interior ocean processes, using assimilation results and computations of representers (elements of the time- and space-dependent model error covariance).

APPROACH

The proposed research involves a systematic continuation of work in progress that has included assimilation of current measurements from moored instruments, surface velocities from an array of HF radars deployed along the Oregon coast, and satellite SSH and SST. Additional data types, including in-situ sections of hydrographic and turbulence observations, have been used to verify results of data assimilation. Studies of the data assimilation methodologies have been focused on the effectiveness of various methods, from simple (albeit suboptimal) "optimal interpolation" to more advanced variational methods. These methods have been utilized with models of increased complexity (linear models, a nonlinear shallow water model, and, presently, a three-dimensional nonlinear model of stratified flows with a turbulence submodel). The data assimilation results have been reported by Scott et al., (2000), Oke et al. (2002a), and Kurapov et al. (1999, 2002, 2003, 2005a, 2005b, 2005c, 2007, 2009, 2010b). These data assimilation studies have been complemented by the dynamical analyses of wind-driven upwelling (e.g., Oke et al., 2002b, 2002c, Kurapov et al., 2005c, Springer et al., 2009), jets in the CTZ (Koch et al., 2010), and internal tides in combination coastal upwelling (Kurapov et al., 2003, 2010a).

Our present approach is based on the use of the variational representer method (Chua and Bennett, 2001, Bennett, 2002) with the nonlinear Regional Ocean Modeling System (ROMS), a free-surface, hydrostatic, primitive-equation model featuring terrain-following coordinates and advanced numerics (Shchepetkin and McWilliams, 2005). The variational method with a nonlinear model requires implementation of a companion tangent linear model and its adjoint counterpart. We have developed and tested our own version of the tangent linear and adjoint codes, AVRORA (Advanced Variational Regional Ocean Representer Analyzer). The dynamics of these stand-alone codes are consistent with the nonlinear ROMS. Availability of our own tangent linear and adjoint codes has allowed us considerable flexibility in the choice of the critical details of our data assimilation system, including (i) ways in which observations are interpreted by the model (data functionals) and (ii) nontrivial hypotheses about error covariances for the corrected initial conditions and atmospheric forcing. Although tangent linear & adjoint ROMS codes have been distributed to the research community, those codes do not allow us similar flexibility. In particular, some of the data functionals that we have tested (e.g., satellite alongtrack SSH slope, HF radar surface current radial component data, any time-averaged data) are not built in ROMS.

In variational data assimilation, the improved ocean state estimate is found by solving a least-squares problem. The optimal ocean state minimizes a cost function defined as a sum of quadratic penalty terms on errors in model inputs (generally including initial conditions, boundary conditions, forcing, also possibly time- and space-distributed errors in model equations) and data-model misfits, all integrated over space and a specified time interval. Formulation of each penalty term requires specification of a corresponding error covariance. In particular, the error covariances for the model inputs can provide smoothing (filtering) of the model correction and also possibly dynamical balances in the corrected fields. To find the optimum solution, we utilize the indirect representer algorithm (Chua and Bennett, 2002) with preconditioning (Egbert et al., 1994) such that the method is applicable with large data sets. As for any variational method applied to a nonlinear dynamical model, the representer method requires repeated solution of the corresponding tangent linear and adjoint systems.

Collaborators in this project include Dr. Kurapov (lead PI), the developer of the AVRORA-ROMS assimilation system and the lead PI. The co-PIs Drs. J. S. Allen and G. Egbert have provide valuable expertise and advice on coastal ocean dynamics and variational data assimilation. Dr. Peng Yu joined this project in February 2009 to help accomplish massive computations and analyses.

WORK COMPLETED

Our studies have been focused on an area centered on the Oregon shelf and CTZ extending between 41-47N and 124-129W (Figure 1). In preparation to assimilation tests, a 3 km resolution ROMS model has been set. Boundary information has been provided from the 9-km resolution Navy Coastal Ocean Model of the California Current System (NCOM-CCS) run at NRL (Shulman et al., 2009). Model studies without data assimilation were leveraged by efforts on the recent NOPP and GLOBEC modeling projects (Springer et al., 2009; Koch et al., 2009). Assimilation tests have been performed at the 6-km horizontal resolution, with focus on the impact of alongtrack SSH altimetry, HF radar surface currents, and satellite SST on surface and subsurface oceanic fields.

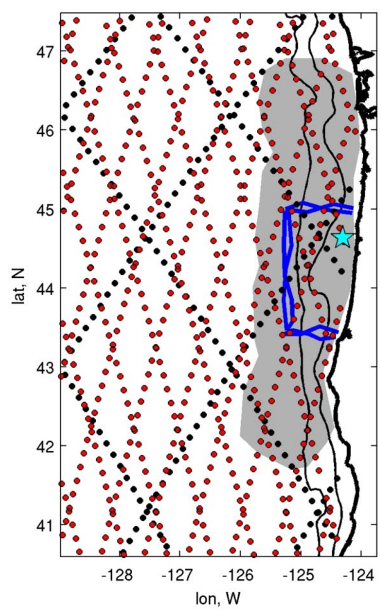

Figure 1. Oregon model domain with locations of observations available recently (dots – altimetry tracks, gray area – HF radar surface currents, blue lines – glider, star – mooring).

Assimilation tests of the AVRORA-ROMS system with actual observations have been performed in a series of relatively short windows (1, 3, or 6 days). In each window, the variational AVRORA system is run to find correction to the initial conditions at the beginning of the window. Then, the nonlinear ROMS is run for the period twice as long as the assimilation interval, to provide the analysis solution (in the assimilation window) and the forecast (to be used as the prior model in the next assimilation window).

The study focused on assimilation of alongtrack altimetry and multi-satellite blended SST (SST data provided by D. Foley from NOAA) has been completed for the study period of 2005, when data from three satellites (Topex, Jason, Envisat) were available (see Figure 1). The manuscript describing this study was submitted to J. Geophys. Res. (Kurapov et al., 2010b) and is currently at the revision stage.

Dr. P. Yu's studies have been focused on assimilation of HF radar surface currents (data provided by P. M. Kosro, OSU). Tests have been completed for summer 2008 and the manuscript is in preparation.

The work assimilating actual observations has been complemented by the analyses of the representers as functions that show zones of influence of assimilated observations. In particular, in these analyses we have looked at the effect of the initial condition error covariance (balanced vs. unbalanced) and also at the propagation of the coastally trapped waves that would carry assimilated information from south to north in a realistic coastal environment.

Data assimilation studies have been complemented by new analyses of the nonlinear ocean dynamics off Oregon. Using leveraging by this and another projects, we have completed the study of the near-surface dynamics of the energetic jet separated in the coastal transition zone off Cape Blanco (south Oregon) (Koch et al., 2010). Kurapov et al. (2010a) have completed the study on the intermittency of the internal tide and its influences on the wind-driven currents on the shelf.

RESULTS

Tests of the AVRORA-ROMS assimilation system with a 6-km resolution coastal ocean model and actual observations of HF radar surface velocities, satellite SSH and SST have demonstrated feasibility of the application of the variational representer-based method in a real-time coastal ocean forecast system. After a preconditioner is built (requiring computation of 100-200 representers, running adjoint and tangent linear jobs in parallel), the convergence rates are good, requiring only 5-15 iterations of the tangent linear and adjoint AVRORA models in each assimilation window to obtain sensible improvement of the initial conditions. With further improvements in parallelization and minimization algorithm, assimilation can be approached at better (2-3 km) resolution.

In the study assimilating satellite alongtrack SSH (Kurapov et al., 2010b), we choose to fit the model SSH slope to the observed slope. This allows avoiding a problem of matching mean levels in the model and observations. As the effect of SSH slope assimilation, surface geostrophic currents are improved. In addition, as verified by comparison with the unassimilated SST, the geometry of the upwelling SST front is improved dramatically (Figure 2). The SSH assimilation positively affects subsurface fields as verified against (limited) hydrographic section data. Later in summer 2005, the outer front is developed, extending parallel to the coast at a distance of approximately 200 km. This front is not reproduced in the limited resolution free-run model (i.e., the model that does not assimilate data) and is not always apparent in the SST maps, since it is rather associated with strong subsurface horizontal density gradient.

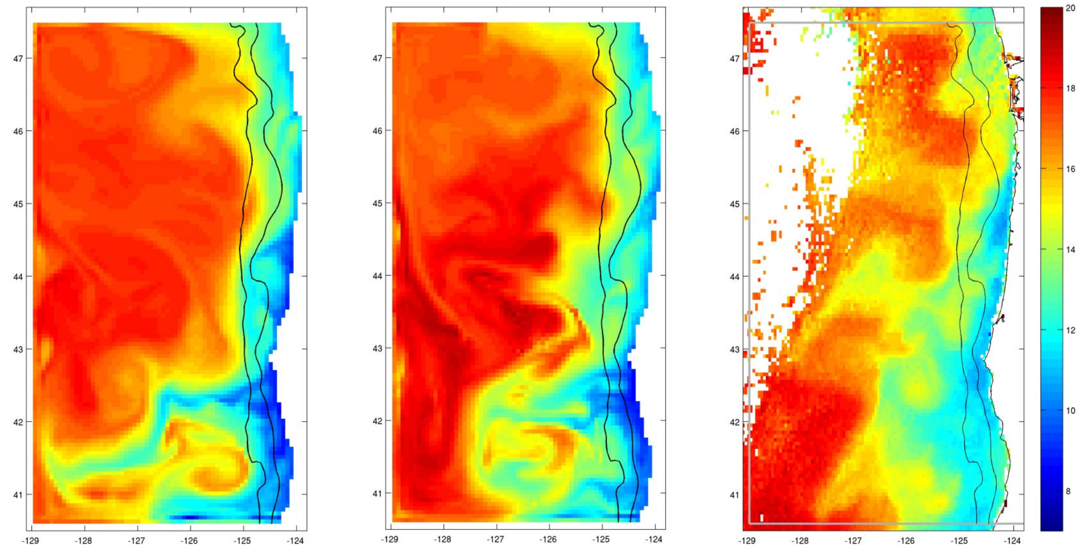

Figure 2. Assimilation of satellite alongtrack SSH data in the coastal transition zone off Oregon qualitatively improves the geometry of the SST front: (left) prior, free run 6-km resolution model, (center) model constrained by assimilation of SSH altimetry beginning June 2005, (right) verification GOES SST daily composite (all images are for 25 September 2005).

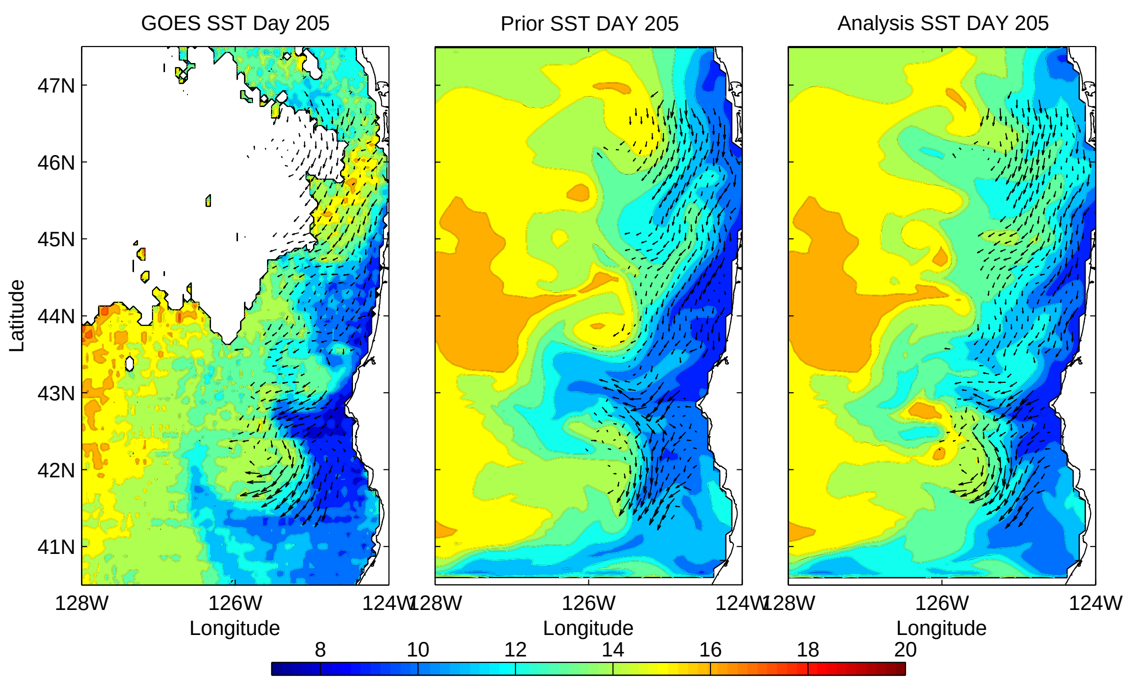

Figure 3. Assimilation of HF radar surface currents helps to improve prediction of not only currents, but also SST: (a) GOES SST (degrees C) and HF radar mapped surface velocities, day 205, 2008, (b) prior model SST and currents (shown at the same locations as observed currents), and (c) forecast (SST and surface currents), after initial conditions on day 201 were corrected assimilating HF radar currents for days 201-203 [P. Yu].

Common for most assimilation methods, the series of analyses solutions exhibits instantaneous finite amplitude steps every time the data assimilation correction to initial conditions is made. This correction can be interpreted as the impulse force added on the r.h.s. of equations. In other words, the DA solutions are generally not dynamically balanced in the time-averaged sense. To evaluate the relative magnitude of the correction in heat content resulting from assimilation of the alongtrack SSH slope or the slope and SST in combination we have performed the analysis of the volume integrated heat budget near coast (including shelf and a part of the interior ocean). We find that the DA correction term is approximately of the same magnitude as the net horizontal advection of heat and atmospheric heat flux. Assimilation of SST in addition to SSH not only improves the SST values, but also helps to reduce the negative bias in the DA correction term.

Assimilation of HF radar surface velocities (daily averaged mapped velocity fields) in a series of 3-day time windows helps to improve accuracy of both analysis and 3-day forecast surface velocity fields. Velocity assimilation also helps to improve the SST structure (Figure 3), as confirmed by statistical comparisons with the unassimilated daily SST fields. Each HF radar provides information on a component of the surface velocity in the direction of the radar. We have run tests assimilating the radial component data and results were similar to the case assimilating mapped (u,v) data. This experiment showed that the variational assimilation system can be used as a new tool for interpolation and mapping HF radar radial component data from a number of radars, to obtain maps of orthogonal velocity components at each location. The advantage of such a mapping tool is that it involves dynamically based scales in the interpolation functions, provides opportunity to synthesize the HF radar data with other data types, and yields accurate forecasts of surface currents and SST.

Success in assimilation of multi-satellite blended SST products can be limited because the noise in the data from each satellite often contaminates the blended product. This is in particularly true of GOES geostationary satellite SST. To alleviate this problem, we have run tests assimilating original hourly GOES data in the variational system. Time- and space-interpolation of these sparse and noisy fields, with projection of the correction to the initial conditions at the beginning of the 3-day time window, allows removing high-frequency noise in the hourly GOES data and filling gaps.

Analyses of the results of the adjoint solution confirmed that the zones of influence of the data are affected by the dynamical processes, including advection and coastally trapped waves (Figure 4).

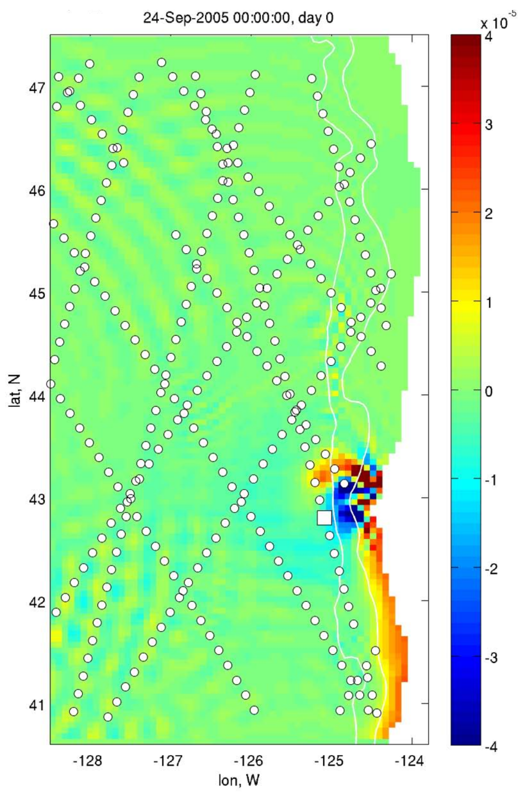

Figure 4. The SSH component of the adjoint solution for the observation of the alongtrack SSH slope at the location shown as square, showing that the error in the observed model variable at later time (t=3 d) co-varies with the initial error in the SSH south of the observational location, as an effect of coastally trapped waves.

IMPACT/APPLICATIONS

Implementation of the variational data assimilation system to the Oregon shelf and adjacent interior ocean has demonstrated value of satellite alongtrack SSH, SST, and HF radar observations for accurate multivariate prediction and forecasting in the coastal ocean. Understanding evolution of the model error, detected by the tangent linear model and its adjoint, helps explain covariability of different processes in the ocean (surface and subsurface, coastal and interior ocean).

TRANSITIONS

The data assimilation system developed in this project has become a part of the pilot real-time Oregon coastal ocean prediction system that provides daily updates of 3-day forecasts in the area centered on the Oregon coast (the real-time work has been leveraged by the NOAA grants). Since August 2009, the data assimilation system works in the real-time operational mode, assimilating HF radar surface current and GOES hourly SST. This prediction system is a part of the regional integrated ocean observing system (IOOS) supported by NOAA via the NANOOS regional association.

RELATED PROJECTS

ONR, "Combining sequential and variational data assimilation". In this new project, we collaborate with Dr. Peter Oke (SCIRO, Australia) to provide comparative tests of optimal interpolation (OI) and variational data assimilation approaches. The study will involve transition of AVRORA-ROMS to our Australian partners.

NSF, "Modeling, assimilation, and analysis of the shelf – open ocean exchange off Oregon." The data assimilation system utilized and advanced in this project will be used to study effect of surface assimilation on subsurface fields and ultimately effects of climate variability on coastal ocean circulation.

NOAA-IOOS, "Enhancing the Pacific Northwest Regional Coastal Observing System (RCOOS) of Northwestern American Network of Ocean Observing Systems (NANOOS)". Data assimilation system improvements will be incorporated in the pilot real-time ocean forecast system run operationally off Oregon with assimilation of satellite alongtrack SSH, GOES SST, and HF radar surface currents.

REFERENCES

Bennett, A. F., 2002: Inverse modeling of the ocean and atmosphere, Cambridge Univ. Press, 234 pp.

Chua, B. S., and A. F. Bennett, 2001: An inverse ocean modeling system, Ocean Modelling, 3, 137-165.

Egbert, G. D., A. F. Bennett, and M.G.G. Foreman, 1994: TOPEX/POSEIDON tides estimated using a global inverse model. *J. Geophys. Res.*, 99(C12), 24 821-24 852.

Koch, A. O., A. L. Kurapov, and J. S. Allen, 2010: Near-surface dynamics of a separated jet in the coastal tranzition zone off Oregon, J. Geophys. Res., 115, C08020, doi:10.1029/2009JC005704.

Kurapov, A. L., J. S. Allen, R. N. Miller, and G. D. Egbert, 1999: Generalized inverse for baroclinic coastal flows, Proc. 3rd Conf. on Coastal Atmospheric and Oceanic Prediction and Processes, 3-5 November 1999, New Orleans, LA, 101-106.

Kurapov, A. L., G. D. Egbert, R. N. Miller, and J. S. Allen, 2002: Data assimilation in a baroclinic coastal ocean model: ensemble statistics and comparison of methods. Mon. Wea. Rev., 130(4), 1009-1025.

Kurapov, A. L., G. D. Egbert, J. S. Allen, R. N. Miller, S. Y. Erofeeva, and P. M. Kosro, 2003: M_2 internal tide off Oregon: inferences from data assimilation, J. Physic. Oceanogr., 33, 1733-1757.

Kurapov, A. L., J. S. Allen, G. D. Egbert, R. N. Miller, P. M. Kosro, M. Levine, and T. Boyd, 2005a: Distant effect of assimilation of moored ADP currents into a model of coastal wind-driven circulation off Oregon, J. Geophys. Res., 110, C02022, doi: 10.1029/2003JC002195.

Kurapov, A. L., J. S. Allen, G. D. Egbert, R. N. Miller, P. M. Kosro, M. Levine, T. Boyd, J. A. Barth, and J. Moum, 2005b: Assimilation of moored velocity data in a model of coastal wind-driven circulation off Oregon: multivariate capabilities, J. Geophys. Res. - Oceans, .110, C10S08, doi:10.1029/2004JC002493.

Kurapov, A. L., J. S. Allen, G. D. Egbert, and R. N. Miller, 2005c: Modeling bottom mixed layer variability on the mid-Oregon shelf during summer upwelling, J. Physical Oceanogr., 35, 1629-1649.

Kurapov, A. L., G. D. Egbert, J. S. Allen, and R. N. Miller, 2007: Representer-based variational data assimilation in a nonlinear model of nearshore circulation, J. Geophys. Res., 112, C11019, doi:10.1029/2007JC004117.

Kurapov, A. L., G. D. Egbert, J. S. Allen, and R. N. Miller, 2009: Representer-based analyses in the coastal upwelling system, Dyn. Atmos. Oceans, 48, 198-218, doi:10.1016/j.dynatmoce.2008.09.002.

Kurapov, A. L., J. S. Allen, and G. D. Egbert, 2010a: Combined effects of wind-driven upwelling and internal tide on the continental shelf, J. Phys. Oceangr., 40, 738-756, doi: 10.1175/2009JPO4183.

Kurapov, A. L., D. Foley, P. T. Strub, G. D. Egbert, and J. S. Allen, 2010b: Variational assimilation of satellite observations in a coastal ocean model off Oregon, J. Geophys. Res., submitted.

Oke, P. R., J. S. Allen, R. N. Miller, G. D. Egbert, and P. M. Kosro 2002a: Assimilation of surface velocity data into a primitive equation coastal ocean model. *J. Geophys. Res*., 107(C9), 3122, doi:10.1029/2000JC000511.

Oke, P. R., J. S. Allen, R. N. Miller, G. D. Egbert, J. A. Austin, J. A. Barth, T. J. Boyd, P. M. Kosro, and M. D. Levine, 2002b: A modeling study of the three-dimensional continental shelf circulation off Oregon. Part I; Model-data comparisons, *J. Phys. Oceanogr.*, 32, 1360-1382, 2002.

Oke, P. R., J. S. Allen, R. N. Miller, and G. D. Egbert, 2002c: A modeling study of the three-dimensional continental shelf circulation off Oregon. Part II: Dynamical analysis, *J. Phys. Oceanogr.* 32, 1383-1403.

Scott, R.K., J.S. Allen, G.D. Egbert, and R.N. Miller, 2000: Assimilation of surface current measurements in a coastal ocean model. *J. Phys. Oceanogr*., 30, 2359-2378.

Shchepetkin, A.F. and J.C. McWilliams, 2005: The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following coordinates ocean model, Ocean Modelling, 9, 347-404.

Shulman, I. and co-authors, 2009: Impact of glider data assimilation on the Monterey Bay model, Deep Sea Res. II, 56, 188–198.

Springer, S. R., R. M. Samelson, J. S. Allen, G. D. Egbert, A. L. Kurapov, R. N. Miller, and J. C. Kindle (2009), A nested grid model of the Oregon Coastal Transition Zone: Simulations and comparisons with observations during the 2001 upwelling season, *J. Geophys. Res.*, 114, C02010, doi:10.1029/2008JC004863.

Weaver, A.T., Deltel, C., Machu, E., Ricci, S., Daget, N., 2005. A multivariate balance operator for variational data assimilation. Q. J. R. Meteorol. Soc. 131, 3605–3625.

PUBLICATIONS

Cipollini, P., J. Benveniste, J. Bouffard, W. Emery, L. Fenoglio-Marc, C. Gommenginger, D. Griffin, J. Hoyer, A. Kurapov, K. Madsen, F. Mercier, L. Miller, A. Pascual, M. Ravichandran, F. Shillington, H. Snaith, P. T. Strub, D. Vandemark, S. Vignudelli, J. Wilkin, P. Woodworth, J. Zavala-Garay, 2009: The role of altimetry in coastal observing systems, OceanObs'09, White Paper. [published]

Kurapov, A. L., J. S. Allen, and G. D. Egbert, 2010: Combined effects of wind-driven upwelling and internal tide on the continental shelf, J. Phys. Oceangr., 40, 738-756, doi: 10.1175/2009JPO4183 [published, refereed]

Koch, A. O., A. L. Kurapov, and J. S. Allen, 2010: Near-surface dynamics of a separated jet in the coastal tranzition zone off Oregon, J. Geophys. Res., 115, C08020, doi:10.1029/2009JC005704 [published, refereed]